Influences of Asymmetric Flow Features on Hurricane Evolution

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LONG-TERM GOALS

It is now recognized that asymmetric processes have a significant impact on the evolution of a symmetric hurricane vortex; the factors that determine the degree to which these processes create changes in hurricane structure and intensity are nevertheless not well understood. Our diagnosis will isolate these factors, especially those leading to rapid deepening.

OBJECTIVES

The broad objective of this research is to investigate the influence of ambient asymmetric flow features, including those associated with upper-level troughs, on the structure and intensification of hurricanes.

The specific objectives of the current effort are:

1. To continue our diagnosis of hurricane structure and intensity change as predicted by the Geophysical Fluid Dynamics Laboratory (GFDL) model using the technique of potential vorticity inversion;
2. To initiate a new study with the full-physics NCAR/Pennsylvania State MM5 numerical model to evaluate the impact of cumulus convection asymmetries on the intensification of a symmetric hurricane vortex.

APPROACH

The approach of our continuing diagnostic analysis involves the use of potential vorticity (PV) to evaluate and understand the impact of ambient environmental flow features on the structure and intensification of hurricanes in real-data numerical forecasts of the Geophysical Fluid Dynamics Laboratory (GFDL). PV is the natural context in which to understand three-dimensional hurricane dynamics. Given a distribution of PV, a balance condition between winds and pressure, a basic state background flow, and appropriate boundary conditions, an inversion can be made to diagnose the complete three-dimensional wind and temperature field. A particularly powerful application of this technique is that of piecewise PV inversion, which allows the evaluation of the wind and temperature fields associated with a given atmospheric feature, such as an upper-level trough. Our research analyzes GFDL hurricane model forecast fields using piecewise PV inversion to isolate the features that have an impact on the development of the model hurricane. The GFDL model is one of the best

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numerical models for hurricane intensification in the world. The study of Shapiro and Möller (2003) was the first to use the method of piecewise PV inversion to diagnose the features asymmetric with respect to the hurricane's center that contribute to tropical cyclone intensification. The foundation of the analysis was the balanced symmetric formulation of Eliassen for a slowly evolving vortex, and its generalization to asymmetric balance (AB; Shapiro and Montgomery 1993). The hurricane in question was Hurricane Opal of 1995, which developed rapidly over the Gulf of Mexico before weakening as it approached the Gulf coast. During its intensification phase the hurricane interacted with an approaching upper-level trough. Although it was one of the most intensely studied hurricanes ever, the cause of Opal's intensification is still a matter of controversy. The earlier study of Möller and Shapiro (2002) diagnosed the symmetric and asymmetric influences on the structure and intensity of the model Opal vortex. On face value this study supported the conclusion that the upper-level trough was not important to the intensification of Opal. As noted in that study, however, piecewise PV inversion is required in order to isolate the contribution of the trough by itself. The results of Shapiro and Möller (2003), which performed such a piecewise inversion, gave no indication that the upper-level trough was a significant contributor to Opal's lower-tropospheric intensification. Our continuing research diagnoses GFDL model forecasts for other hurricanes in order to determine if the results for Opal were an anomaly or the rule.

The approach of our new study with the MM5 model involves the diagnosis of idealized numerical experiments to evaluate the impact of cumulus convection asymmetries on the intensification of a symmetric hurricane vortex. Diabatic heating associated with deep cumulus convection creates PV anomalies. Shapiro (2000) used a simple three-layer numerical model including a convergence-based convective parameterization scheme to understand the role of cumulus convection and the atmospheric boundary layer in the interactions between PV asymmetries and a hurricane vortex. This study showed that convection plays an important role in determining how a hurricane responds to the anomalies in its environment. The short-term response is constrained to the extent that moving the PV anomalies radially inward or outward had no qualitative effect on the change of the symmetric hurricane vortex. The three-layer model with its convergence-based convective scheme is limited, however, in the realism of its representation of convection, particularly in the context of longer-term evolution. Our new research uses the NCAR/Pennsylvania State full-physics nonhydrostatic multi-level numerical model (MM5) to evaluate and extend results from the simpler three-layer model in a more realistic setting. The impact of convective heating asymmetries and PV generation on a symmetric hurricane vortex will be evaluated. The impact of diabatically-generated asymmetries on hurricane intensification, and the duration, location, amplitude, radial and vertical structure of the convective anomalies will be diagnosed.

In both the continuing diagnosis of the GFDL model with real-data forecast and the new study with idealized numerical experiments with the MM5 model, the PI, Dr. Lloyd Shapiro, works in close collaboration with Dr. Dominique Möller, who is also supported with the ONR grant.

WORK COMPLETED

The paper Shapiro and Möller (2003) on the influence of atmospheric asymmetries on the intensification of Hurricane Opal has appeared in print. An analysis of the atmospheric features that contributed to the intensification of Hurricane Bertha of 1996 in a GFDL model forecast has been completed. The results of this study are described in the following section. Model forecast fields have

been obtained from GFDL for a forecast of Hurricane Erin of 2001. Analysis of the impact of environmental features that contributed to this hurricane's intensification has begun.

The model code development required for the MM5 model itself, including specification of the structure and duration of the diabatic convective forcing, and for diagnostics of the MM5, including output of azimuthal-mean quantities and asymmetric deviations, have been completed. Preliminary results from a benchmark experiment are described briefly in the following section. Vorticity and angular momentum budget diagnostics to evaluate the interaction between the asymmetries and the symmetric vortex are under development.

RESULTS

Hurricane Bertha of 1996 intensified rapidly as it approached the east coast of the United States. During the 12 hours just before landfall on the U.S. east coast the hurricane's maximum winds increased from 70 to 90 knots. Some authors have indicated that this increase may have been associated with the influence of an approaching mid-latitude atmospheric trough. Warm sea surface temperatures just off the U.S. coast may also have contributed to the intensification. The GFDL numerical hurricane forecast model closely approximated Bertha's intensification rate at this time. A similar piecewise PV inversion technique to that for Hurricane Opal, presented in Shapiro and Möller (2003), was used to diagnose the reason for the intensification of Hurricane Bertha in the GFDL model forecast. The result of the piecewise PV inversion for Hurricane Bertha demonstrates diagnostically for the first time that an approaching mid-latitude upper-level trough had a significant positive impact on a hurricane's intensification. This result is in contrast to Hurricane Opal, where it was concluded that an upper-level trough had a small influence on the hurricane's rapid deepening.

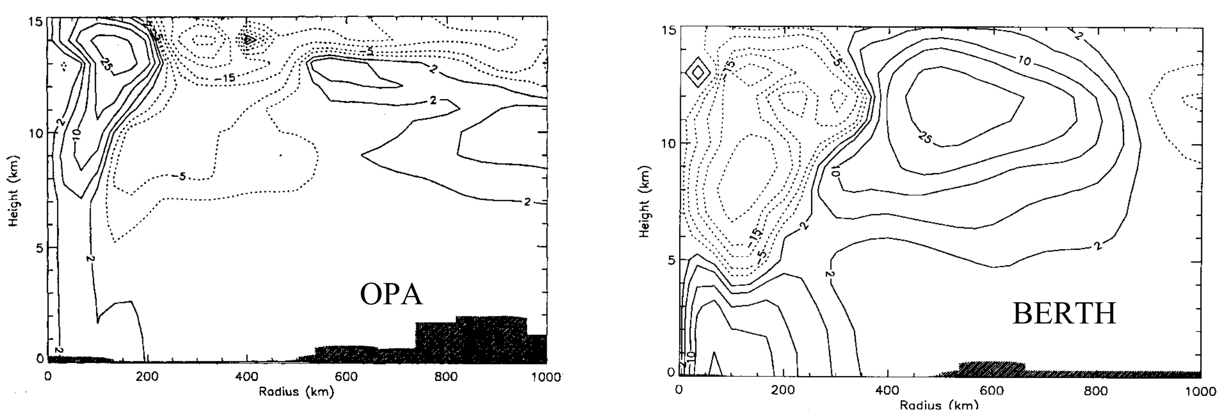

Figure 1. Symmetric tangential wind tendency associated with upper-level outer-radii PV anomaly for GFDL forecasts of Hurricane Opal at 1800 UTC 3 October 1995 (left panel) and Hurricane Bertha at 0600 UTC 12 July 1996 (right panel). Contours are ±2, ±5, ±10, ±15, ±25, ±40, ±70 ms^{-1}***/day (positive contours solid, negative contours dashed). The region below the surface is shaded.***

The contrast between the result for Opal and that for Bertha is shown in Figure 1. This figure shows a radial-height presentation of the tendency of the symmetric tangential wind associated with PV asymmetries restricted to upper levels and outer radii, where the corresponding atmospheric troughs are located. The symmetric wind tendencies are derived from Eliassen's symmetric balanced

formulation forced by eddy heat and momentum fluxes using temperatures and winds derived from the asymmetric balance (AB) formulation. For both hurricanes the static stability has been reduced in the eyewall region to correspond to moist saturated ascent. For Hurricane Opal (left-hand panel of Fig. 1) the surface inner-core symmetric tangential wind tendency associated with the upper-level outer-radii PV anomaly is less than $4\,\mathrm{ms}^{-1}$/day. Since at the time of the analysis Opal was intensifying at about 30 ms^{-1}/day, it is natural to conclude that the upper-level trough did not have a significant contribution to the hurricane's intensification. For Hurricane Bertha (right-hand panel of Fig. 1), by contrast, the surface inner-core symmetric tangential wind tendency associated with the upper-level outer-radii PV anomaly is on the order of $25\,\mathrm{ms}^{-1}$/day. This intensification rate is comparable to the observed intensification rate at the time of the analysis of about 20 ms^{-1}/day. Thus the conclusion is that the upper-level atmospheric trough had a significant positive impact on Hurricane Bertha's intensification. A benchmark experiment has been completed with the MM5 numerical model. Since the model horizontal resolution for this experiment is relatively coarse (with a minimum grid spacing of 15 km), both explicit moist processes and parameterized convective heating with the Betts-Miller scheme are included. A symmetric hurricane model vortex is first spun up on an f-plane. An azimuthal wavenumber two diabatic heating asymmetry centered at the radius of the maximum heating in the symmetric vortex is then added for one hour. The asymmetric diabatic heating creates PV anomalies, which then influence the evolution of the symmetric vortex. The changes in the symmetric vortex at early times appear similar to those in previous studies without convection in two and three dimensions (Möller and Montgomery, 1999, 2000) and with a convergence-based convective parameterization in a three-layer model (Shapiro 2000). In particular, the symmetric vortex intensifies at lower levels near the radius of maximum wind. The longer-term evolution of the symmetric vortex is more complex. Analysis of the results is continuing.

IMPACT/APPLICATIONS

The results of the diagnostic studies with the GFDL numerical hurricane forecast model will be used to isolate the reasons why some atmospheric upper-level troughs appear to weaken a hurricane while others appear to intensify one. The results will also help to elucidate reasons for good and bad forecasts from the GFDL model, and thereby aid in improvement of this and other numerical hurricane forecast models. The results of the idealized numerical experiments to study the impact of cumulus convection asymmetries on the intensity of a symmetric hurricane vortex have the potential to improve forecasts of rapid deepening and eyewall replacement cycles by establishing the conditions under which such processes are favored.

RELATED PROJECTS

The diagnosis of the influence of asymmetric flow features on hurricane intensification in the Geophysical Fluid Dynamics Laboratory (GFDL) model is being made in collaboration with Dr. R. Tuleya of GFDL (http://www.gfdl.gov/hurricane.html). The utilization of the MM5 model is being made in collaboration with the ONR-supported research project of Prof. R. Smith at the University of Munich (http://www.meteo.physik.uni-muenchen.de).

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